LOAD DIVERSION METHOD AND APPARATUS FOR HEAD PROTECTIVE DEVICES

This application claims priority to U.S. Provisional Patent Application 60/416,312, filed by Steven M. Madey on October 4, 2002, and titled "Load Diversion Method and Apparatus for Head Protective Devices", the entirety of which is incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates generally to helmets and other head protective devices, and more particularly to methods and apparatus for lessening the transfer of oblique impact forces to an individual wearing such a device.

BACKGROUND OF THE INVENTION

Traumatic brain injury (TBI) is the leading cause of death and long-term disability in the USA among people below 45 years of age. In the U.S. alone, each year over two million people sustain traumatic brain injury, with a financial impact of about $4 billion annually. To alleviate the impact of TBI, a variety of task-specific helmets have been introduced. To date the use of helmets is no longer confined to high-risk occupational scenarios and motorcyclists, but appreciates wide-spread acceptance and even legal prescription for common recreational and sports activities, such as bicycling. Given the large number of helmets in use, even a small improvement in the protective effect of helmets will evoke a considerable benefit to the health status of the general population.

Helmets are designed to protect the brain and skull during an impact. Conventional helmets perform this function by distributing and absorbing a portion of an impact's kinetic energy by deforming (elastically or inelastically) a compliant layer. Typically, a permanently attached outer shell distributes the impact load, and an interior-padding layer absorbs impact energy. For an activity such as bicycling, the capabilities of the shell and padding layer

represent a compromise between the need to maximize energy absorption and minimize object penetration, practical and aesthetic limitations on weight and thickness, and other factors such as style, aerodynamics, head cooling, etc.

Figure 1 shows a traditional recreational sports hard shell helmet 20 in longitudinal cross-section. A padding layer 22 surrounds and is generally shaped to fit (usually with insert foam padding to adjust for a comfortable fit) the protected portion of the wearer's head. A hard outer shell 24 of glass-reinforced plastic, polycarbonate thermoplastics, or the like, is adhered to padding layer 22. A helmet retention system (e.g., straps 26) allows the user to attach the helmet securely to the head, usually with a chinstrap and increasingly with a suspended rear strap or member that aligns the helmet properly on the wearer's head. The helmet retention system usually attaches directly to outer shell 24.

Figure 2 shows, in cross-section, a micro-shell helmet 27, which has largely replaced the traditional hard shell helmet for most bicycle applications (primarily due to reduced weight). Helmet 27 uses a liner 22 manufactured from expanded polystyrene beads, designed to absorb kinetic energy upon impact. A tape strip (not shown) running along the lower edge of a plastic microshell 28 secures the plastic microshell to the exterior of liner 22. A helmet retention system 26 generally attaches to and/or loops through holes in liner 22. Upon substantial impact, the plastic microshell may tear apart or split, and the underlying liner may crack or shatter as it absorbs energy. Consequently, microshell helmet manufacturers typically recommend replacement after a single crash, even if helmet integrity appears uncompromised.

Particularly with microshell helmet designs, large cross-section integrated vents have been incorporated into the helmet as a selling feature. Figure 3 illustrates a vented microshell helmet 30 in longitudinal cross-section. Although similar in construction to helmet 27, microshell 28 and liner 32 contain substantial shaped voids or ports (e.g., 34) that ostensibly

function as vents to allow some airflow through the helmet. The remaining polystyrene struts 32 may be quite thick, in order to restore at least part of the structural integrity lost due to voids 34.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may be best understood by reading the disclosure with reference to the drawing, wherein:

Figures 1, 2, and 3 show longitudinal cross-sections of three prior art recreational helmet designs;

Figures 4A and 4B contain cross-sections of a helmet according to an embodiment of the invention, shown respectively in longitudinal and transverse cross section;

Figure 5 shows construction and functional detail of the embodiment of Figures 4A and 4B;

Figures 6 and 7 show construction and functional detail of another embodiment employing a different interface layer;

Figures 8A and 8B illustrate yet another embodiment of the invention, which incorporates air vents and uses an interface layer disposed near the outer helmet shell;

Figures 9A and 9B depict an interface layer comprising a lamellar structure, respectively under no-load and tangential force conditions;

Figures 10A and 10B depict an interface layer comprising adjacent rigid shells, respectively under no-load and tangential force conditions;

Figures 11A, 11B, and 11C depict an interface layer employing thin connecting members that pass through the interface layer, respectively under no-load, small tangential force, and large tangential force conditions;

Figure 12 illustrates one possible displacement response characteristic for a non-linear interface layer according to an embodiment of the invention;

Figure 13 shows the construction of an embodiment wherein connecting members are disposed around the periphery of air vents in a helmet; and

Figure 14 demonstrates test results for a standard helmet and an embodiment of the invention when subjected to an oblique impact with a concrete surface.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The increased use of bicycle helmets over the past decade does not seem to have reduced the incidence rate of traumatic brain injury per bicyclist, but has coincided with a 51% increase in the rate of head injuries per active cyclist. This phenomenon may only insufficiently be explained by a more aggressive riding attitude among bicyclists, based on a misleading sense of security provided by helmets. It is now recognized herein that this seeming incongruity may be accounted for, at least in part, by three specific deficiencies in the design of bicycle helmets.

First, prior bicycle helmets are primarily designed to distribute and absorb impact loads by means of a padding layer underlying a generally dome-shaped semi-rigid shell. This design is effective in distributing a focused impact over a larger area of the cranium to reduce the risk of skull fractures. Given geometric constraints of the padding layer, however, its ability to absorb a significant amount of energy is limited. Subsequently, the remaining energy will be transformed into acceleration of the head, where the amount and duration of head acceleration directly correlates to the extent of traumatic brain injury. Therefore, the design of contemporary bicycle helmets may effectively reduce the incident of skull fractures, but falls short in protecting its user from the disabling consequences of traumatic brain injury.

Second, bicycle helmets are primarily designed to absorb impact loads by means of energy-absorbing and load-distributing layers. This design greatly increases the distance of the impact site (i.e., the semi-rigid outer shell) from the apparent rotation axis of the head

around the neck, therefore providing an effective lever arm to transform the tangential component of an oblique impact to the helmet into an angular acceleration of the head. Since the brain is most susceptible to angular acceleration of the head, current helmet designs do not protect the head from closed-head traumatic brain injury due to angular acceleration, but may instead contribute to it.

Third, bicycle helmets are primarily designed to absorb impact loads by means of a padding layer underlying a generally dome-shaped semi-rigid shell. Traditional helmets (for motorcycling, skateboarding, etc., see Figure 1) employ a rigid, dome-shaped outer shell that tends to hold its shape and slide during impact. Modern bicycle helmets (see Figures 2 and 3) have a smooth, semi-rigid, non-continuous surface made of a considerably thin plastic layer. This thin shell primarily improves appearance and aerodynamics but is essentially unsuitable to bear or divert typical impact loads present during head impacts. As a method for energy absorption, the helmet surface (in combination with an underlying foam core) will deform to congruency with the surface geometry of the impacting object. Instead of diverting an impacting object and its associated kinetic energy, this congruency can lead to a prolonged impact duration, and the corresponding form lock between the impacting object and the helmet will cause an effective transfer of energy to the head instead of an effective energy diversion.

In summary, the inefficacy of bicycle helmets to divert tangential impact energy may dramatically limit their ability to decrease the amount and magnitude of head acceleration. The use of contemporary helmets may therefore be ineffective to reduce the incidence of closed head traumatic brain injury, and may in fact increase the stresses to the cervical spine. In contrast, the present invention provides a means of diverting and/or absorbing tangential impact energy before that energy is translated to the wearer's head and neck.

A first embodiment of the present invention is illustrated as helmet 40 of Figures 4A

and 4B, in longitudinal and transverse cross-section. Helmet 40 comprises an inner helmet layer (e.g., an energy-absorbing layer) 41, a helmet retention system (e.g., straps 42 and foam padding inserts, not shown) to affix inner helmet layer 41 to a wearer's head, an outer helmet layer (the combination of energy-absorbing layer 43 and microshell 44 in this embodiment), and an interface layer 45 disposed between the inner and outer helmet layers.

The inside surface of energy-absorbing layer 43 forms a cavity with a spherical curvature. Likewise, the exterior of energy-absorbing layer 41 has a spherical curvature with a slightly smaller radius than that of layer 43. During assembly, interface layer 45 is interposed between layers 41 and 43 and secured (e.g., by adhesive bonding) to the outer surface of layer 41 and the cavity surface of layer 43.

Interface layer 45 can provide, in essence, a spherical bearing of low/controlled friction to allow relative displacement between layers 41 and 43 under oblique impact conditions. Accordingly, assembled helmet 40 allows an inner helmet layer to remain affixed to a wearer's head, while allowing potentially large rotational displacement of outer layers 43 and 44 with respect to the inner layer (and the wearer's head) in response to an applied force.

Figure 5 illustrates further construction and operational details for this first embodiment. In this embodiment, interface layer 45 consists of a distensible flexible envelope filled to a desired thickness with a viscous medium 52. Viscous medium 52 can be, for example, a gel (e.g., silicone), a liquid (e.g., aqueous solutions, an oil, or other lubricant), and/or a filler comprising solid spherical particles. Segment 50 of the envelope is secured to the inner surface of outer helmet layer 43; segment 54 of the envelope is secured to the outer surface of inner helmet layer 41. Along the bottom edge of the interface, a "slack" section of the envelope can be left unattached, to readily permit some limited rotation, with any remaining rotation relying, for example, on distention of the envelope and/or partial separation of the envelope from the attached helmet layers. The slack section can also

distend to displace portions of the viscous medium and absorb compression loads placed on the envelope.

Figure 5 depicts the application of an oblique force vector F to the outer helmet 44. Force vector F can be decomposed into two component vectors, one (F_{norm}) normal to the helmet surface at the point of impact, and the other (F_{tang}) acting along the helmet surface. The magnitude of F_{tang} will depend on the coefficient of friction between layer 44 and the striking object. It is noted, however, that large F_{norm} values will generally cause substantial deformation of layers 43, 44 when such use a traditional microshell construction, thereby increasing friction and F_{tang}.

In response to force vector F_{tang}, envelope 45 allows a rotational displacement R of the outer helmet layers with respect to the inner helmet layers, absorbing and/or deflecting at least a portion of a rotational component that would otherwise be communicated to the wearer's head. At the same time, envelope 45 may absorb a portion of force vector F_{norm} as viscous medium 52 pressurizes, forcing envelope 45 to distend along its periphery and allow some of viscous medium 52 to be displaced from between layers 41 and 43. Geometric and constitutive properties of the envelope and viscous medium, such as medium thickness and viscosity, the elastic modulus and area of unattached envelope at the helmet periphery, and the force required to separate the envelope from other helmet layers, can be adapted to meet specific shock-absorbing and shear-deflecting/absorbing properties for specific helmet applications.

An additional advantage that can be achieved in at least some embodiments is improved absorption of force vector F_{norm} due to the displacement of the impact site during impact. Materials such as foam will completely compress, or "bottom out", near the impact site for some value of F_{norm}. To reduce this phenomenon in a prior art helmet, typically one increases the foam thickness. In an embodiment with a displaceable outer layer, however, the

area of the inner layer directly under the impact site will generally be changing over the duration of the impact. This movement increases the area over which the inner foam layer is being compressed, thus potentially delaying and/or preventing bottoming out.

Figure 6 illustrates a second interface layer construction technique. In Figure 6, interface layer 45 consists of a hyper-elastic gel that can be bonded to the inner surface of layer 43 and the outer surface of layer 41 to ensure helmet integrity during normal use. The gel allows rotational displacement—and potentially separation—of the outer helmet assembly with respect to the inner helmet assembly when a tangential impact force is applied to the outer helmet. Further, depending on gel properties, layer 45 may act to absorb a portion of F_{norm} and/or further distribute that force before it is applied to inner helmet layer 41. Geometric and constitutive properties of interface layer 45, such as its thickness, viscosity, and/or elastic modulus can be adapted to meet specific shock-absorbing and shear-deflecting/absorbing properties for specific helmet applications.

Figure 7 illustrates the same helmet cross-section shown in Figure 6, but with a different impact force vector F typical of a cyclist going over her handlebars and hitting the pavement headfirst. In Figure 7, then, the resultant F_{tang} vector causes the outer helmet assembly to rotate forward to partially shield the wearer's face. Thus although not necessary in every embodiment, the helmet geometry can be designed to extend a portion of the outer helmet layers 43, 44 down past the original edge of the helmet due to displacement upon impact, potentially providing increased facial protection in a crash. Such a feature is not necessarily limited to forward rotation—with an appropriate design and a large displacement, the outer helmet layer can generally be designed to act as an extended shield to protect areas of the head that would otherwise not be covered by a protective shell.

In the preceding embodiments, the interface layer was interposed between two, e.g., expanded polystyrene layers. Figures 8A and 8B illustrate another helmet embodiment 80,

respectively in transverse and longitudinal cross section, wherein an interface layer 84 is interposed between a rigid outer shell 85 and an energy-absorbing layer 81, 82. Preferably, rigid outer shell 85 is constructed of a material such as glass-reinforced or carbon fiber-reinforced plastics/resin systems, polycarbonate, titanium, or perhaps high-density polyethylene. Although such an embodiment can potentially use a microshell, a microshell may tend to crack and tear upon impact, exposing the interface layer and allowing the impact surface to ablate the underlying interface layer. Depending on interface layer construction, this characteristic may or may not be tolerable—if not, a hard shell that resists deformation and tearing can be used.

Figures 8A and 8B show other features that may be desirable in a particular application. For instance, helmet 80 incorporates air vents (e.g., 86), with the interface layer attached to support pillars 81, 82 of the helmet. Helmet 80 also illustrates that the inner and outer helmet layers need not have coextensive head coverage (see hidden line 83 in Figure 8B, showing the lower edge 83 of the interface layer 84. In practice, a design may limit the extent of the interface to helmet areas that are most likely to strike the ground so as to cause rotational acceleration, e.g., the frontal helmet quadrants, provided that sufficient clearance is allowed for outer helmet assembly displacement upon impact.

Finally, helmet 80 shows a tail appendage 87 attached to the outside of shell 85. Tail appendage 87 can be used to impart aerodynamic or aesthetic qualities to the helmet without impeding the displacement function of interface layer 84. Other constructs can have, for instance, part of shell 85 covering part of interface layer 84 and part of shell 85 covering part of tail appendage 87, with tail appendage 87 attached directly to a part of interface layer 84.

In addition to the filled envelope and hyper-elastic gel embodiments already described, other interface layer constructions are possible. Figure 9A shows a section of a helmet with an outer helmet layer 90, an inner helmet layer 92, and an interface layer 94

disposed between layers 90 and 92. Interface layer 94 comprises a lamellar structure of hyper-elastic columns 96. Columns 96 buckle under an impact force to absorb impact energy. And as shown in Figure 9B, application of a force F_{tang} to one of the helmet layers results in a relative displacement *d* as columns 96 bend and stretch in response to the tangential force, thereby deflecting and partially absorbing the tangential force.

The interface layer can also comprise multiple solid shell layers, as shown in Figure 10A. Although such layers can be buried between energy-absorbing layers within the helmet, Figure 10A shows an interface layer comprised of two solid shell layers 106 and 108 near the helmet exterior. Solid shell layer 106 attached to an outer helmet layer 100. Solid shell layer 108 attaches to an inner helmet layer 102. The solid shell layers can be designed to slide readily across each other in response to a force F_{tang} applied to the outer helmet layer (see Figure 10B), thereby deflecting the force instead of transmitting it to the inner helmet layer. Solid shell layers 106 and 108 can be constructed, for example, of materials that exhibit a low coefficient of friction, such as polyethylene or polytetrafluoroethylene (PTFE), and can further employ an intermediate lubricant to further reduce friction between layers 106 and 108.

Optionally, solid shell 106 can function alone as both outer shell 100 and as part of the displaceable interface of the helmet in some embodiments.

Shells 106 and 108 can be held together initially in a fixed position, e.g., by peripheral tape or another connecting member (to be explained below) designed to shear upon impact, thereafter allowing free (or freer) motion between the two shells.

With an interface layer that easily displaces in response to even slight tangential forces, for example, it may be desirable to restrict such displacement prior to an impact event. Accordingly, Figure 11A shows an interface layer construction with a primary interface medium 114 disposed between an outer helmet layer 110 and an inner helmet layer 112.

Intermittent connecting members 116 pass through primary interface medium 114 to join the inner and outer helmet layers. The connecting members 116 are depicted as integral to inner helmet layer 112, but can, in the alternative: be integral to outer helmet layer 110; contain sections integral to both the inner and outer helmet layers that are engaged/connected during assembly; or be completely separate from the inner and outer helmet layers until connected during assembly.

Preferably, connecting members 116 substantially prevent displacement of the outer helmet layer with respect to the inner helmet layer under normal usage and handling, thereby imparting a unitary feel to the helmet. For instance, Figure 11B illustrates the response of the interface layer 114 with connecting members 116 when a tangential force F_{tang} less than a design shear force F_S is applied to outer helmet layer 110. A small displacement *d* is observed as connecting members 116 resist the propensity of interface layer 114 to displace.

Connecting members 116 are designed to shear or otherwise disconnect, however, when a tangential force F_{tang} exceeds the design shear force F_S. The design shear force F_S is preferably set low enough that connecting members 116 fail at tangential impact forces indicative of a crash—and lower than a force that would cause a potentially injurious head acceleration. As shown in Figure 11C, once connecting members 116 fail, interface layer 114 can allow a relatively large displacement *D*.

In some embodiments, it may not be necessary that members 116 actually connect the inner and outer helmet layers. For instance, members 116 can substantially impede large displacements of a hyper-elastic layer by virtue of protruding through a portion of the layer's thickness and extending along the layer perpendicular to the direction in which displacement is to be constrained.

Another way to view an interface layer with connecting and/or displacement-impeding members is as an interface layer that responds non-linearly to tangential forces.

Figure 12 contains a graph 120 showing displacement of an outer layer 122 with respect to an inner layer 124 as a function of an applied tangential force F_{tang}. A connecting/displacement-impeding member 128 within an interface layer 126 initially resists tangential forces less than F_{PEAK} (shown for illustrative purposes at about 0.6 KN). Forces less than F_{PEAK} cause a relatively small and temporary displacement, with the helmet elastically restoring itself to zero displacement once the force is removed. Once F_{PEAK} is exceeded, however, member 128 fails, causing an inelastic change in the response characteristic of interface layer 126, which can then move through relatively large displacements in response to tangential forces much smaller than F_{PEAK}.

Connecting members can take a variety of forms. For instance, Figure 13 illustrates a cross-section of a vented helmet 130. Helmet 130 contains connecting members 139 molded into an inner helmet layer 132 at the periphery of air vents and along the outer periphery of the inner helmet layer 132 where it joins the outer periphery of an outer helmet layer 135. Accordingly, the outwardly facing surface of inner helmet layer 132 contains formed depressions, between connecting members 139, into which an interface medium 138 can be inserted. Outer helmet layer 135 is subsequently positioned as shown and adhered to both interface medium 138 and connecting members 139. Thus the cross-sectioned inner helmet support pillar 131 adheres to cross-sectioned outer helmet support pillar 134, encapsulating a portion of interface medium 138 and forming one surface of an air vent and a lower helmet exterior surface. Cross-sectioned inner helmet support pillar 133 adheres to cross-sectioned outer helmet support pillar 136, encapsulating another portion of interface medium 138 and forming two air vent surfaces. Similar construction can be used in the rest of the helmet. Thus helmet 130 contains an encapsulated interface medium 138 and has the outward appearance of a prior art helmet. Under a large impact force, however, connecting members 139 readily fail, allowing the outer helmet assembly to rotate about the inner helmet assembly

due to the previously described properties of interface medium 138.

Figure 14 shows the results of a guided free-fall drop test comparing a standard bicycle helmet with the same helmet type equipped with a low-friction interface layer. One standard helmet was modified by attaching a distensible silicone-filled envelope to the outside of the outer helmet layer. A segment of an outer helmet layer from an identical helmet was then attached to the outside of the silicone-filled envelope, forming a low-friction interface (LFI) helmet.

Drop tests on the standard and modified helmets were then performed by attaching the helmets to a headform with a hinged "neck" joint and dropping each helmet onto a concrete anvil. The concrete anvil had a top surface angled at 30 degrees to horizontal to simulate an oblique impact that might occur in a bicycle crash where a rider is launched onto pavement.

Peak linear acceleration, peak angular acceleration, and neck moment were measured for the standard and LFI helmets. Upon impact, the inner assembly of the LFI helmet translated parallel to the surface of the anvil, inducing a backward rotation of the head around the neck joint. The standard helmet did not slide on the anvil surface, and therefore induced a head flexion moment. The head flexion moment further form-locked the standard helmet to the anvil, prevented sliding of the standard helmet. Accordingly, compared to the standard helmet, the LFI helmet exhibited an 87% smaller peak linear acceleration, a 68% lower peak angular acceleration, and a 74% decrease in neck moments.

Helmet materials are widely selectable, depending on design. By way of example, energy-absorbing layers can be constructed of polystyrene foam, expanded polystyrene foam, hexagonal honeycomb structures, and the like. Some outer shell materials are: titanium / titanium alloys; epoxies; fiberglass-epoxy composites; carbon-fiber-epoxy composites; polyethylene; polycarbonate; and fluoropolymers. Some potential interface layer materials are: silicon-based gels; hyper-elastic materials (e.g., rubber based on latex, silicon, or

polyurethane); and sliding interface layer pairs of polyethylene, fluoropolymers, or polycarbonate. Those skilled in the art will recognize from the preceding disclosure the large number of potential combinations of these, as well as other materials not explicitly listed, that can be combined in an embodiment of the present invention.

One of ordinary skill in the art will recognize that the concepts taught herein can be tailored to a particular application in many other advantageous ways, and that the embodiments presented are merely exemplary. Some preferred embodiments utilize an interface layer with a spherical curvature, thus allowing rotational displacement of an outer helmet assembly in a plurality of axes of rotation. Other arrangements are possible, however. For instance, the helmet layers could contain features, such as longitudinal channels or ridges, that constrain displacement to fore-and-aft rotation. Or, particularly as the arc length of the interface decreases, it could depart significantly from a spherical curvature while still allowing considerable displacement. A displaceable outer helmet section that primarily protects the forward helmet quadrants could even employ a canted planar interface. Although the innermost layer in the described embodiments was an energy-absorbing layer, that layer can alternately be a hard layer, with the helmet retention system providing head cushioning.

Although the specification may refer to "an", "one", "another", or "some" embodiment(s) in several locations, this does not necessarily mean that each such reference is to the same embodiment(s), or that the feature only applies to a single embodiment.